

COSMIC RAYS FROM GAMMA RAY BURSTS IN THE GALAXY

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Introduction: Gamma-ray bursts (GRBs) are brief flashes of γ -ray light emitted by sources at cosmological distances. Recent observations link GRBs with star-forming galaxies and a rare type of evolved high-mass star that explodes as a supernova when its core collapses to a black hole. Most core-collapse supernovae, by contrast, form neutron stars. In either case, the supernova explosion ejects a remnant that expands into and shocks the interstellar medium. These shock waves accelerate high-energy cosmic-ray protons and ions. The supernovae that form neutron stars are thought to accelerate cosmic rays to energies reaching 10^{14} eV. The much more energetic GRB shock waves, with speeds very close to the speed of light, are thought to accelerate the highest energy cosmic rays, with energies reaching and exceeding 10^{20} eV.

Because the Milky Way is actively making young high-mass stars, GRBs will also occur in our Galaxy. The rate of GRBs in the Milky Way is very uncertain because of the lack of precise knowledge about the opening angle of GRB jets, but it could be as frequent as once every 10,000 years. Acceleration of cosmic rays by GRB jets, and propagation of cosmic rays through the magnetic field of our Galaxy and across the universe, can explain the spectrum of cosmic rays at the highest energies (Fig. 7).¹

Over the age of the Galaxy, there is a good chance that a nearby powerful GRB, with a jet oriented toward Earth, could have lethal consequences for life. It has recently been argued² that such an event contributed to the Ordovician extinction event 440 Myrs ago. Understanding cosmic-ray propagation and effects on materials is important to estimate radiation damage on spacecraft, cosmic-ray effects on humans in space, and the origin of cosmic rays.

Methodology: To assess cosmic ray transport from a GRB, a 3D propagation model was developed to simulate the sequence of irradiation events that occurs when a GRB jet is pointed toward Earth. The cosmic rays move in response to a large-scale magnetic field that traces the spiral arm structure of the Galaxy, and they diffuse through pitch-angle scattering off magnetic turbulence waves. The magnetic field of the Galaxy is modeled as a bisymmetric spiral for the Galaxy's disk and a dipole magnetic field for the Galaxy's halo. The evolution of the particle momentum is found by solving the Lorentz force equation. A Monte Carlo simulation of pitch-angle scattering and diffusion was developed that takes into account the energy dependence of the cosmic-ray mean free path.

Figure 8 displays the cosmic-ray halo that surrounds a GRB source 14,000 years after the GRB event. The geometry of the radiations is modeled by twin radial jets of cosmic rays with a jet-opening half-angle of 0.1 radian. A conical shell forms as a result of protons and neutron-decay protons with energies above 10^{18} eV. Beamed cosmic-ray protons and neutrons that decay near the GRB form "wall" features, as seen in the view from overhead for a transverse jet.

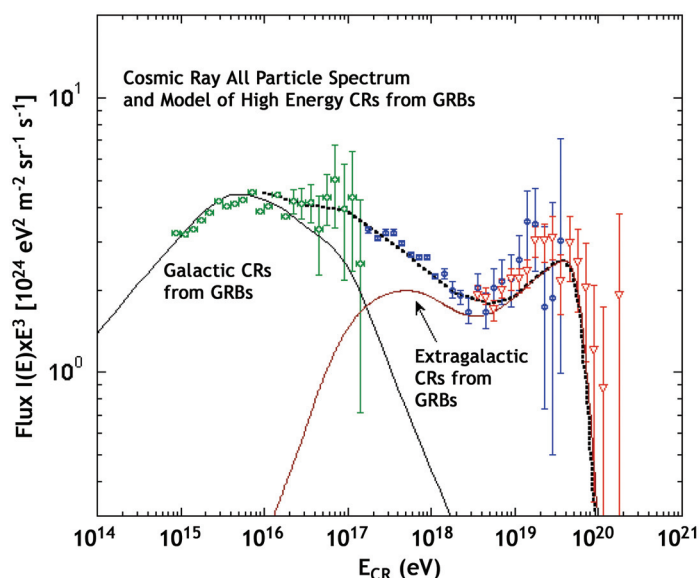


FIGURE 7

Fit of a model¹ to cosmic-ray data from the KASCADE, Hi Res-I and Hi-Res II cosmic ray experiments (see Ref. 1 for sources of data). High-energy cosmic rays are accelerated by GRBs in the Galaxy and throughout the universe in this model.

This is a consequence of the rapid diffusion along the field vs the slower cross-field diffusion, and by magnetic mirroring effects of the jetted cosmic rays in the spiral arm structure of the Galaxy.

Discussion: About once every several hundred million years, the Earth is blasted by GRB photon and neutral radiations of sufficient intensity to have significant effects on the biota. Such an event might have been responsible for trilobite extinction in the Ordovician epoch through destruction of plankton.²

The prompt high-energy X rays, γ rays, and cosmic rays produce cascade UV flux and odd nitrogen compounds that destroy the ozone layer, possibly accounting for the pattern of extinction events. Cosmic rays from GRBs would also have affected biological evolution from DNA radiation damage by the elevated ground-level muon fluxes induced by prompt and delayed cosmic rays. These radiations could have initiated the ice age that followed the onset of the Ordovician extinction event.

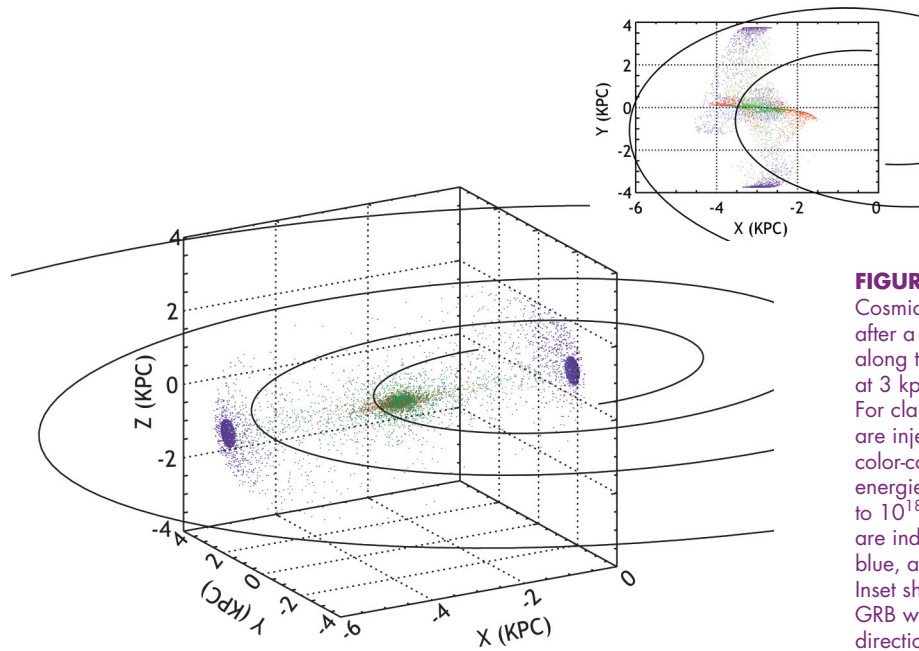


FIGURE 8

Cosmic-ray halo formed 14,000 years after a GRB, with radial jets oriented along the Galactic plane, that took place at 3 kpc from the center of the Galaxy. For clarity, equal numbers of cosmic rays are injected per decade, with cosmic rays color-coded by energy. Cosmic rays with energies in the ranges 10^{16} to 10^{17} , 10^{17} to 10^{18} , 10^{18} to 10^{19} , and 10^{19} to 10^{20} , are indicated by red, yellow, green, light blue, and dark blue symbols, respectively. Inset shows view from overhead for a GRB with jets oriented in the transverse direction.

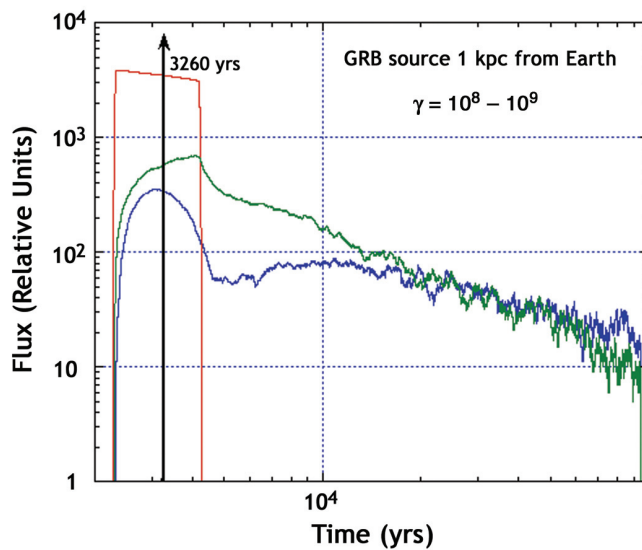


FIGURE 9

Fluxes of 10^{17} to 10^{18} eV cosmic rays received at Earth from an on-axis GRB that occurred 3,260 light years away. The red, green, and blue curves represent cosmic-ray neutrons, neutron-decay protons, and protons, respectively. The prompt flux actually lasts for minutes to hours, rather than the 2,000 yrs indicated by the figure, which reflects the approximations of the numerical method.

Figure 9 shows the time-dependence of the flux of neutrons and protons from a GRB source located 3,260 light years from the Earth. The prompt flux has greater lethality and effect compared to the delayed cosmic rays. The combined radiations could make a two-phase event that produced the Ordovician extinction event. Our simulations also show unusual effects that arise from a propagation model that combines both ray tracing and diffusive pitch-angle scattering. Astronomy missions with significant NRL involvement, such as NASA's Gamma ray Large Area Space Telescope (GLAST), will be able to test this GRB model for cosmic-ray origin.

[Sponsored by ONR and NASA]

References

- ¹ S.D. Wick, C.D. Dermer, and A. Atoyan, "High Energy Cosmic Rays from Gamma-Ray Bursts," *Astroparticle Phys.* **21**, 125-148 (2004).
- ² A.L. Melott, B.S. Lieberman, C.M. Laird, M.V. Medvedev, B.C. Thomas, J.K. Cannizzo, N. Gehrels, and C.H. Jackman, "Did a Gamma-Ray Burst Initiate the Late Ordovician Mass Extinction?" *Internat. J. Astrobiology* **3**, 55-61 (2004).